# NOVEL SOLUTIONS FOR MITIGATING DROUGHT IMPACT AND RESTORING SOIL FUNCTIONALITY IN AGRICULTURE
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# *SOLUȚII NOI PENTRU ATENUAREA IMPACTULUI SECETEI ȘI RESTABILIREA FUNCȚIONALITĂȚII SOLULUI ÎN AGRICULTURĂ*

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## ABSTRACT

*Drought and soil degradation represent critical challenges to sustainable agriculture and global food security, because they limit crop productivity and disrupt ecosystem services. The paper explores novel solutions designed to mitigate the impacts of drought and restore soil functionality in agricultural systems. The proposed approaches integrate innovative soil amendments, such as biochar and compost-based bioproducts, with advanced water conservation techniques and biological interventions aimed at improving soil structure, fertility, and moisture retention. Furthermore, the study examines the role of microbial inoculants and organic matter management in enhancing soil resilience to climatic stressors. This paper focuses on the analysis of case studies that illustrate notable advances in mitigating the effects of drought and improving the quality of agricultural soils through the use of unconventional and innovative technologies. The results highlight the effectiveness of integrating biological, physical, and chemical strategies, carefully adapted to specific site conditions. The adoption of these novel approaches has the potential to enhance the resilience of agricultural systems to climate variability, while simultaneously supporting productivity and long-term sustainability. This research supports the development of climate-smart agricultural approaches that harmonize productive farming with long-term environmental sustainability. This paper synthesizes and critically evaluates the most effective and current strategies identified in recent literature, offering a comprehensive overview aimed at advancing efforts to combat climate change.*

## REZUMAT

*Seceta și degradarea solului reprezintă provocări critice pentru agricultura durabilă și securitatea alimentară globală, deoarece limitează productivitatea culturilor și perturbă serviciile ecosistemice. Lucrarea explorează soluții noi concepute pentru a atenua impactul secetei și a restabili funcționalitatea solului în sistemele agricole. Abordările propuse integrează amendamente inovatoare ale solului, cum ar fi biocharul și produsele bio pe bază de compost, cu tehnici avansate de conservare a apei și intervenții biologice menite să îmbunătățească structura, fertilitatea și retenția umidității solului. În plus, studiul examinează rolul inoculanților microbieni și al gestionării materiei organice în îmbunătățirea rezistenței solului la factorii de stres climatic. Această lucrare se concentrează pe analiza studiilor de caz care ilustrează progrese notabile în atenuarea efectelor secetei și îmbunătățirea calității solurilor agricole prin utilizarea tehnologiilor neconvenționale și inovatoare. Rezultatele evidențiază eficacitatea integrării strategiilor biologice, fizice și chimice, atent adaptate la condițiile specifice ale amplasamentului. Adoptarea acestor abordări noi are potențialul de a spori rezistența sistemelor agricole la variabilitatea climatică, sprijinind în același timp productivitatea și sustenabilitatea pe termen lung. Această cercetare sprijină dezvoltarea unor abordări agricole inteligente din punct de vedere climatic care armonizează agricultura productivă cu sustenabilitatea mediului pe termen lung.*

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## INTRODUCTION

The increasing severity and frequency of drought events, coupled with ongoing land degradation, have emerged as major threats to agricultural sustainability and global food security. Drought impacts are manifesting not only as temporary reductions in crop yield but also as long-term degradation of soil quality (*Teliban et al., 2022; Vlăduţ et al., 2017; Vlăduţ et al., 2018*), structure, and ecosystem function (*Nadeem et al., 2018; Bularda et al., 2020; Cârdei et al., 2021a; Cârdei et al., 2021b; Biriș. et al., 2021; Marin et al., 2024; Vlăduţ et al., 2013; Vlăduţ et al., 2023a; Nenciu, et al., 2022a-d).* Understanding this problem requires a critical examination of the underlying drivers and consequences, situated within the broader context of environmental, social, and technological systems (*Khan et al., 2024; Nenciu et al., 2020; Oprescu et al., 2023; Voicea, et al., 2024*).

The degradation of soils under drought conditions is fundamentally driven by the combined effects of natural climate variability and human activities. Extended periods of low precipitation, intensified by climate changes, result in declining soil moisture, reduced infiltration, and loss of organic matter, which collectively impair the soil's capacity to support plant growth (*Ashraf et al., 2019; Mircea et al., 2020; Ciobotaru et al., 2013*). Furthermore, inappropriate land management practices, such as overgrazing, excessive tillage, monocropping, and the removal of vegetative cover, exacerbate the vulnerability of soils to erosion, compaction, and salinization. These processes diminish the productive capacity of soils and undermine their role as carbon sequestration sources and regulators of hydrological cycles (*Oncescu et al., 2025; Tienda et al., 2024; Tarniţă et al., 2025*). The complexity of this domain is highlighted by the intricate interplay between biophysical and socio-economic factors, which collectively shape both the underlying challenges and the pathways to potential solutions. From a biophysical perspective, soils exhibit considerable heterogeneity in terms of texture, structure, organic matter content, and microbial dynamics-attributes that critically influence their capacity to withstand and recover from drought stress. Furthermore, the variability among agro-ecological zones leads to diverse soil-water-plant interactions, necessitating tailored, site-specific management strategies to enhance resilience. Concurrently, socio-economic constraints-such as insecure land tenure, insufficient access to credit and financial services, weak extension and advisory systems, and gaps in supportive policy frameworks—significantly limit the ability of farmers, particularly smallholders and resource-poor producers, to implement sustainable land management practices (*Cujbescu et al., 2023; Vlăduț et al., 2024; Nenciu et al., 2014*). These interdependencies underscore the need for integrated approaches that simultaneously address environmental, technical, and socio-economic dimensions to effectively mitigate soil degradation and enhance agricultural sustainability.

An in-depth exploration of the domain also reveals that knowledge and technology transfer remain critical bottlenecks. Although innovative technologies and equipment for drought mitigation and soil restoration have been developed and tested in experimental settings, their widespread adoption has been slow. Farmers often face barriers such as high initial costs, lack of technical know-how, and uncertainties about the long-term benefits of these innovations. Bridging this gap requires not only technological improvements, but also institutional support mechanisms, capacity building, and participatory approaches that engage farmers as active stakeholders (*Stan et al., 2024; Vlăduţ et al., 2022; Vlăduț et al., 2023b; Voicea et al., 2022*).

From a systems perspective, soil degradation and drought impact multiple dimensions of sustainability-environmental, economic, and social-requiring holistic and interdisciplinary solutions. Restoring degraded soils entails more than physical or chemical amendments; it involves rebuilding soil biological activity (*Tudora et al., 2024a; Tudora eta al., 2025*), enhancing water retention, improving nutrient cycling, and increasing biodiversity (*Nenciu et al., 2023; Voicea et al., 2021*). Similarly, mitigating drought impacts goes beyond providing irrigation infrastructure, encompassing water-use efficiency, crop diversification, and landscape-level interventions that enhance resilience.

Furthermore, the domain's complexity is heightened by the uncertainty inherent in climate projections and the non-linear, often irreversible, nature of soil degradation processes. Tipping points can be crossed, beyond which soil recovery becomes extremely difficult or impossible. This underscores the urgency of implementing preventive and adaptive measures before critical thresholds are reached.

Considering these challenges, it becomes apparent that a critical analysis of the problem must move beyond symptom treatment to address root causes and structural constraints. It calls for an integrative approach that combines scientific research, technological innovation, policy reform, and stakeholder participation. The development and deployment of innovative equipment and systems for soil restoration and drought mitigation must be embedded within broader strategies that promote sustainable land use, strengthen institutional capacities, and build adaptive capacity at the community level.

This research therefore lays the groundwork for identifying and evaluating such innovative solutions by providing a nuanced understanding of the problem and the intricacies of the domain. By critically examining both the drivers of soil degradation and the barriers to implementing effective solutions, better interventions can be designed, that are not only technically sound but also socially acceptable, economically viable, and environmentally sustainable.

Addressing the dual challenge of drought and soil degradation requires recognizing that soils are living systems embedded within complex socio-ecological networks. Their restoration is not merely a technical task but a transformative process that demands systemic thinking, long-term commitment, and collective action. The subsequent sections of this article build on this critical analysis to propose and discuss specific technologies, equipment, and integrated systems that align with these principles and offer tangible pathways toward sustainable land management and agricultural resilience.

The most recent solutions proposed for mitigating the effects of drought and restoring soil functionality in agriculture are, in most cases, either developed within an overly theoretical framework, lacking direct correlation with on-field realities, or based on highly specific experimental models that are difficult to replicate or adapt to other agricultural systems. This lack of general applicability limits technology transfer and the large-scale adoption of such solutions. Moreover, the scientific literature is considerably fragmented, being dominated by studies addressing related topics - such as fertilization, land rehabilitation, or water management - but which fail to provide integrated and novel solutions dedicated exclusively to improving soil quality.

Furthermore, truly interdisciplinary approaches are often absent or insufficiently supported by relevant experimental data adapted to current agro-ecological conditions. As a result, there is an urgent need for the development of scalable technologies, tested under real-world conditions, that can respond to the multiple challenges imposed by climate change. High-impact solutions should encompass not only the biological and physicochemical aspects of soil but also innovative technological components that allow real-time monitoring and adaptation. Another major obstacle is the lack of standardized methodologies that would enable comparative assessment of the effectiveness of various technologies.

Therefore, our objective is to critically analyze the scientific literature and identify the most relevant and impactful research in this field. Despite the growing body of research on climate change mitigation and soil management, there remains a notable lack of consolidated evaluations that systematically compare the effectiveness of different strategies within this domain.

- **Context and research approach**

The review employed a systematic selection process, identifying relevant research papers through comprehensive searches of major academic databases (Web of Science, Scopus, ScienceDirect) using predefined keywords related to climate change and soil management. Inclusion criteria prioritized recent peer-reviewed studies emphasizing the practical applicability of mitigation strategies, while studies lacking field experimental research were excluded.

Numerous strategies have been proposed and investigated in recent years to mitigate the negative effects of climate change on agriculture, however all these measures remain insufficiently structured and synthesized. Consequently, their practical application by farmers is often limited, fragmented, or ineffective. The lack of a coherent and accessible framework impedes the adoption of innovative practices that could effectively enhance resilience and sustainability in agricultural systems. Addressing this gap is crucial, given the accelerating rates of soil degradation, declining fertility, and the expansion of desertified areas, which together threaten global food security and rural livelihoods (*Rugege et al., 2017; Alvar-Beltrán et al. 2021; Vlăduțoiu et al., 2025*).

The main objective of the current research paper is to present, in a unified, scientifically grounded, and practically oriented manner, a set of innovative technologies, equipment, and integrated systems that have demonstrated potential in mitigating drought impacts and restoring degraded agricultural soils. By consolidating knowledge from recent research and field applications, the paper aims to provide a comprehensive synthesis that facilitates decision-making at farm level and informs policy development.

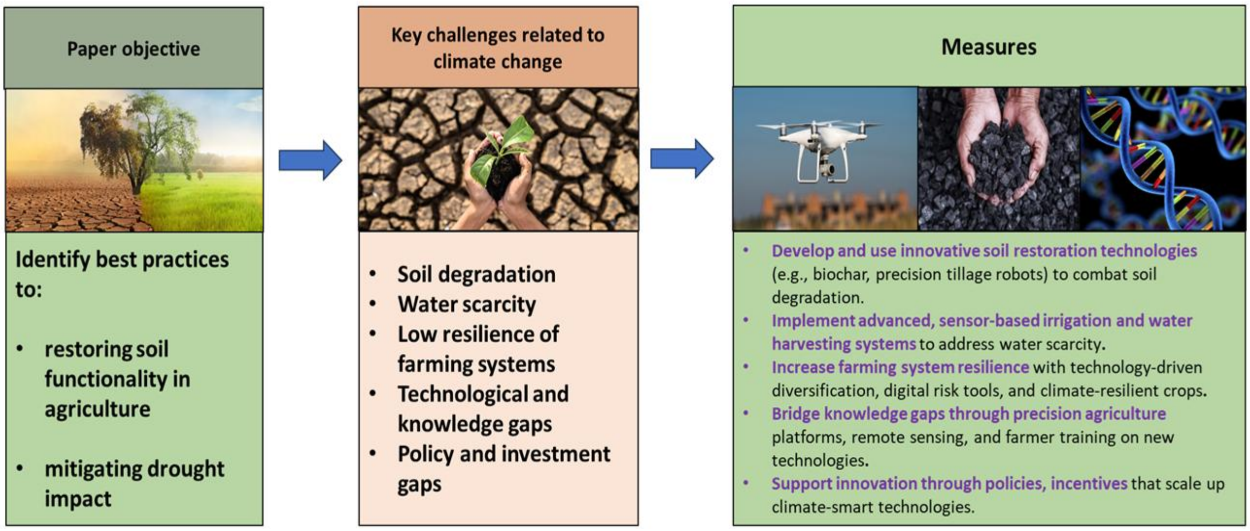


**Fig. 1 - Experimental approach for mitigating drought impact and restoring soil functionality in agriculture**

Furthermore, the article highlights the critical importance of soil as a highly valuable resource underpinning agricultural productivity and ecosystem services. Climate-induced stressors, such as prolonged droughts, increased evapotranspiration, and extreme weather events, exacerbate existing pressures from unsustainable land use, overgrazing, and excessive tillage. Without targeted interventions, these processes can lead to irreversible losses in soil structure, organic matter, and biodiversity (*Teiba et al., 2024; Popa et al., 2023*).

The paper also seeks to explore the synergies between technological innovation and traditional soil conservation practices, demonstrating how modern precision agriculture tools, remote sensing, and automated irrigation systems can complement time-tested measures like mulching, crop rotation, and cover cropping. Emphasis is placed on cost-effectiveness, scalability, and adaptability to diverse agro-climatic zones, ensuring that the proposed solutions are accessible not only to large-scale commercial farms but also to smallholder and subsistence farmers.

In addition, the discussion includes an assessment of implementation barriers, such as financial constraints, lack of technical knowledge, and institutional weaknesses, proposing pathways to overcome these challenges through capacity building, policy incentives, and multi-stakeholder collaboration. Ultimately, this article aspires to contribute to the broader discourse on sustainable land management by offering actionable insights and evidence-based recommendations for reversing soil degradation trends and enhancing agricultural resilience in the face of climate change.

✓ ***The Impact of Climate Change on Agricultural Productivity***

Global agricultural productivity is changing as a result of climate change, both directly and indirectly. Reduced crop yields, decreased soil fertility, and increasing unpredictability in farming techniques are all being caused by rising temperatures, changing growing seasons, altered precipitation patterns, and an increase in the frequency of extreme weather events. Temperature changes, droughts, and floods are examples of extreme weather phenomena that are progressively upsetting worldwide agricultural systems. Crop yields, food security, and the livelihoods of farmers worldwide are all directly threatened by these events. The frequency and intensity of these events are predicted to increase in tandem with climate change, presenting serious obstacles to agriculture and the ability to continue producing food in a sustainable manner.

Extreme events like drought and aridity are a result of global climate change, which has been increasingly prevalent in recent years. It has been demonstrated over time that severe drought episodes in a given location not only result in high rates of death and economic losses but also negatively impact the biological system, human life, economic activity, and water supplies (*Fye et al., 2010 Schwalmet al., 2017; Popescu et al., 2012*).

Agriculture is characterized by a complex web of structures and interactions among diverse components, producing concerns over its future viability, especially in a climate that offers considerable hazards to food security. As a result, it's critical to assess how climate change is negatively affecting agricultural productivity and develop fresh approaches to these problems (*Rahman et al., 2018*).

Numerous global-scale assessments have been conducted regarding the impact of climate change on agriculture; however, these assessments frequently fail to capture the uncertainties inherent in climate projections and fail to account for important factors like changes in pest and disease dynamics and extreme weather events. Furthermore, different criteria lead to dramatically varied estimations of future risks about the best ways to quantify the impacts of climate change on drought from an agricultural perspective (*Gornall et al., 2010*).

✓ ***The Impact of Extreme Weather Events on Global Agriculture***

The study of the impact of future climate change on agriculture has become one of the hottest issues in the current field of climate change research. This is because there is no guarantee about the future impact of climate change on crops and the importance of agricultural production (*Xiao et al., 2020; Zilli et al., 2020*). Extreme events, such as drought, floods, and heat waves, can affect agricultural production by decreasing crop yields, livelihoods, and community food security.

Rapid climate change is having a significant impact on agricultural production, which is essential for human survival and development *(Annie et al., 2023*). It also disrupts the ecological balance and has an impact on the prevention and management of agricultural diseases and pests (*Yang et al., 2023; Tudora et al., 2022; Tudora et al., 2024b*). In addition, soil degradation and lack of land resources have been caused by climate change, which has had a negative effect on the progress of agricultural production in the long term (*Eekhout et al., 2022*).

In addition to the areas directly affected by the event, other areas around the world may be affected by indirect consequences, such as rising food prices and declining exports of agricultural products.

Understanding the impact of extreme weather events on crop yields in both the current and previous climates is essential to ensure and optimize yields in a changing climate (*Vogel et al., 2019*). Strong international cooperation and inventive solutions are needed to meet this challenge. The joint efforts of nations can promote the development of sustainable technologies and significantly reduce greenhouse gas emissions by combating the effects of climate change.

✓ ***Mitigation approaches***

Several studies have identified viable methods to minimize the effects of climate change on agricultural productivity using new approaches and agricultural practices. Among the most frequently explored approaches are conservation agriculture, precision farming, crop diversification, and integrated nutrient - water management. Researchers usually emphasize the importance of adapting crop varieties to changing climatic conditions, improving soil health through organic amendments, and implementing climate-smart irrigation techniques.

Additionally, there is growing interest in agroecological practices and regenerative agriculture, which not only reduce greenhouse gas emissions, but also increase carbon sequestration in soils and vegetation. The integration of digital technologies, such as remote sensing and AI-based monitoring, further supports the optimization of resource use and risk mitigation in the face of weather variability. Numerous studies also underline the role of policy frameworks and farmer education in scaling up these adaptive practices. Ultimately, a multidisciplinary approach combining agronomy, environmental science, and socio-economic analysis is essential for developing resilient agricultural systems in the era of climate change.

Emission avoidance strategies that generate a positive carbon sequestration and improve input usage efficiency include conservation agriculture, controlled traffic, precision farming, and soil-specific management. Climate change adaptation options in agriculture include producing massive quantities of biomass even in the context of rising temperatures, less effective precipitation, an increase in the frequency and severity of extreme events, and increased pest and pathogen pressure (*Yang et al, 2023*). The net balance between carbon gains and losses determines the dynamic equilibrium of the soil carbon pool. The application of organic amendments (such as compost, manure, and biochar), the deposition of carbonaceous substances (both organic and inorganic) by wind and water, and biomass inputs (such as plant and animal waste) all contribute to carbon gains. Thus, the addition of carbon in the soil stabilizes it against microbial attack through the formation of structural aggregates, the transformation of simple organic compounds into complex humic substances, the transfer of carbon into the subsoil (illuviation), and the transformation of that carbon into decomposition-resistant substances (recalcitration). Grazing, harvesting, and burning all physically remove biomass from the soil, which results in carbon losses. Additionally, decomposition, mineralization, leaching of dissolved carbon molecules, and rapid erosion (from wind, water, tillage, and gravity) all reduce soil carbon. By making carbon gains larger than carbon losses, the aim is to produce a positive carbon budget (*Lal et al., 2010*).

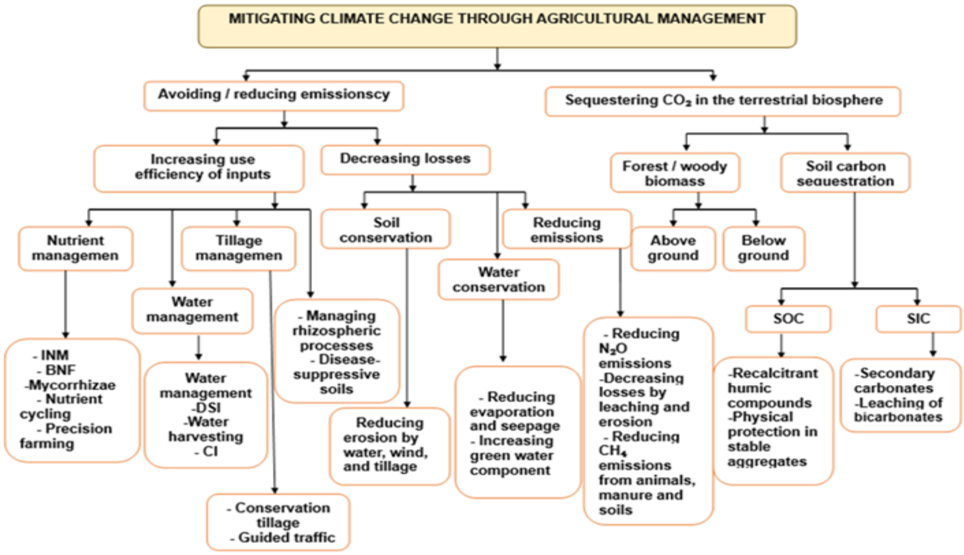


**Fig. 2 - Sustainable agricultural techniques to mitigate climate change**

**Where: INM = Integrated Nutrient Management; BNF = Biological Nitrogen Fixation; DSI = Deficit Soil Irrigation; CI = Conjunctive Irrigation (the combined use of surface water and groundwater resources for irrigation); SOC = Soil Organic Carbon; SIC = Soil Inorganic Carbon (carbon stored in soils as carbonates and bicarbonates)*

Agriculture and global warming are interconnected, forming a two-way relationship in which agricultural practices both influence and are influenced by climate change. Modern farming technologies contribute significantly to greenhouse gas emissions and environmental degradation, yet they also hold immense potential to mitigate climate change through the adoption of sustainable techniques, as illustrated in Figure 2.

By implementing practices such as efficient nutrient and water management, conservation tillage, and improved soil carbon sequestration, agriculture can play a pivotal role in reducing its ecological footprint. Enhancing soil health, preserving water resources, and increasing biomass also contribute to atmospheric carbon removal and climate resilience. Furthermore, these strategies not only curb emissions, but also improve long-term productivity, food security, and ecosystem stability. The diagram highlights how targeted interventions-both above and below ground create synergies between agricultural productivity and environmental stewardship. Ultimately, transforming agriculture into a climate-smart sector is essential for meeting global sustainability goals and ensuring the resilience of food systems in the face of climate change.

Figure 3 illustrates key strategies for enhancing agricultural adaptation to climate change, in order to maintain productivity at advanced levels, but in a sustainable way.

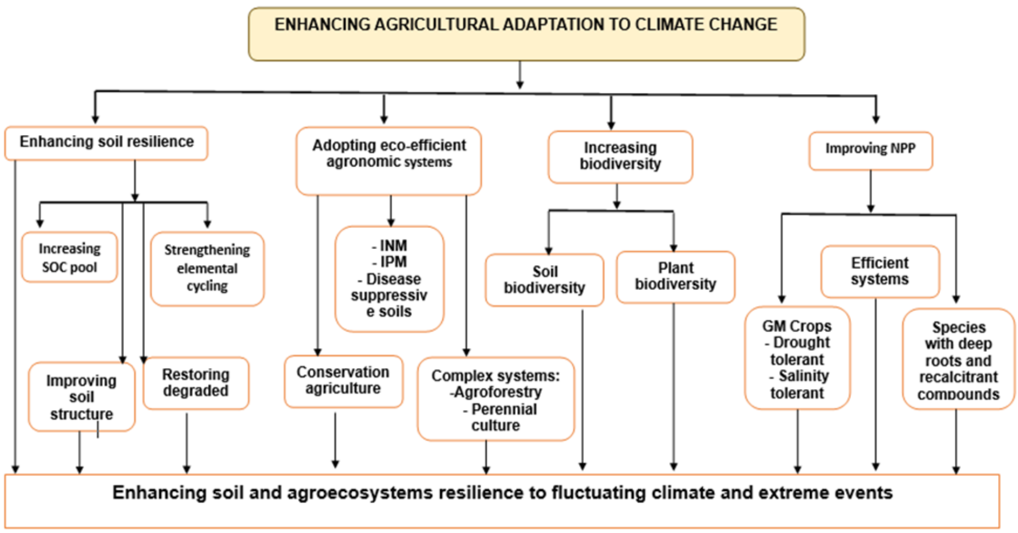


**Fig. 3 - Sustainable agricultural techniques to mitigate climate change**

**Where: SOC = Soil Organic Carbon; INM = Integrated Nutrient Management (a balanced approach to plant nutrition that combines organic, inorganic, and biological sources of nutrients to improve efficiency and sustainability); IPM = Integrated Pest Management ( a strategy for controlling pests and diseases using a combination of biological, cultural, physical, and chemical tools in a way that minimizes risks to health and the environment); NPP = Net Primary Productivity (the rate at which plants accumulate biomass (carbon) through photosynthesis minus the carbon they respire, representing the growth and productivity of vegetation); GM Crops = Genetically Modified Crops (Crops that have been genetically engineered for drought or salinity tolerance, pest resistance, or improved yield)*

As showed above, a major pathway is enhancing soil resilience, achieved by increasing the soil organic carbon (SOC) pool, improving soil structure, and restoring degraded soils. Strengthening elemental cycling and improving soil health are critical to maintaining soil productivity under stress conditions. Therefore, adopting eco-efficient agronomic systems is another cornerstone, which includes integrated nutrient management (INM), integrated pest management (IPM), and fostering disease-suppressive soils.

These practices are supported by conservation agriculture, which minimizes soil disturbance and preserves resources. Increasing biodiversity is highlighted through both soil and plant biodiversity, which improve ecosystem functions and stability.

Complex systems such as agroforestry and perennial cropping systems contribute significantly to biodiversity and resilience. However, the measures must not affect productivity. Improving net primary productivity (NPP) is also essential, and can be performed without affecting productivity by deploying genetically modified (GM) crops that are drought and salinity tolerant. In addition, efficient production systems that optimize resource use and reduce losses further enhance climate resilience.

These approaches build synergistic benefits for soils, plants, and ecosystems. They aim not only to mitigate the negative impacts of climate change, but also to sustain agricultural productivity in the long term. The integration of these practices strengthens agroecosystem sustainability and food security.

- **The chemical challenge in agriculture: understanding the impact of agrochemicals on soil health and sustainability**

About 95% of global food production is supported by soil, a non-renewable resource that provides ecosystem services such as biomass production, pollutant removal, and mass and energy transfer between continents. Soil natural resources are threatened by unsustainable management practices and climate change, especially in the Mediterranean region, where growing populations, rapid land-use changes, associated socio-economic activities and climate change are putting significant pressure on shallow soils. Even though there is evidence that soil is highly susceptible to degradation and desertification, it is unclear how severe soil degradation is (*Ferreira et al., 2022*).

To meet the food needs of a rapidly growing global population, the use of various agrochemicals is essential for contemporary agriculture. These products contribute significantly to increasing the economical and efficient production of crops. Agrochemicals are used in agriculture to bridge the gap between food production and consumption to meet the growing demand for food. However, the improper use of agrochemicals causes environmental degradation and raises a number of problems for soil health and agricultural ecosystems. Microorganisms help with nutrient cycling and improve soil health and crop productivity. Soil degradation caused by the excessive use of agrochemicals threatens global livelihoods, soil health and food security. In addition to numerous other biotic and abiotic factors, including soil characteristics and crop varieties, agrochemicals have a significant impact on how microbial populations and communities of microorganisms in soil evolve (*Mandal et al. 2020*).

Soil degradation causes landslides, floods, desertification, water contamination, and a decline in food production globally. Meanwhile, there are a number of direct consequences that affect the agricultural sector every day.

In agriculture, the continuous use of agrochemicals can also have other harmful effects such as: soil salinization and acidification, loss of organic matter, soil compaction, loss of biodiversity, etc.

Preventing land degradation will help keep farmland productive enough to feed an expanding population. Land conservation supports ecosystems and biodiversity. In addition, healthy soils sequester carbon dioxide and help mitigate climate change.

A global adoption of soil conservation practices will protect natural resources and ensure the long-term viability of agriculture (*Nunes et al., 2020; * ESDAC*).

It is also essential to adopt alternative treatment solutions, such as plant extracts, which are rich in bioactive compounds, to reduce dependence on synthetic chemicals in agriculture (*Tăbărașu et al., 2024 a, b; Isticioaia et al., 2024; Stan et al., 2024*).

- **Climate change challenges in agriculture**

Climate change affects crops in many ways, but some important factors stand out due to their significant influence and are widely acknowledged as crucial in the specialized literature. The aforementioned factors, which have an immediate impact on plant development, soil health, and water availability, include rising temperatures, changing precipitation patterns, and an increase in the frequency of extreme weather events.

A comprehensive grasp of these crucial elements is important for evaluating the vulnerability of agricultural systems and designing appropriate adaptive solutions. In this section, the most significant climate-related elements that promote losses in crop yield and agricultural sustainability will be analyzed, as discovered in recent studies.

**Table 1**

**Climate change impact on agriculture: key factors and responses**

| Phenomenon | Impact | Counteraction | References |
|---|---|---|---|
| **Heat stress on crops** | - Higher average temperatures lead to heat stress in crops, reducing photosynthesis and slowing growth rates.<br>- Reduce plant resistance to diseases. | - Development of heat stress tolerant crop plants through environmental and genetic interactions;<br>- Use of detection sensors to expand genetic databases in abiotic stress breeding programs;<br>-The use of viruses, bacteria and fungi to enhance the resistance of crops to heat stress;<br>-Use of transgenic crops | Nadeem, 2018; Teiba, 2024; Kan, 2023; Ashraf, 2019; Khan, 2024; Mukhtar, 2023; Duarte, 2024; Fanai, 2024 |
| **Accelerated growth cycles** | Warmer temperatures can cause crops to mature faster, reducing the time available for grains, fruits, or vegetables to fully develop, thus decreasing overall productivity and nutritional quality.<br>- The occurrence of eutrophication | - Use of physical, chemical and biological control techniques such as ultrasound, micro-current or ultraviolet, coagulation/flocculation;<br>- Physical shading is a method by which the process of photosynthesis is prevented or slowed down, thus preventing growth.<br>- Adsorption and ion exchange method | Wang, 2024; Moore, 2021 Yang, 2020; Simkin, 2020; Foste, 2021; Hwang, 2020; Akinnawo, 2023; Ajala, 2023 |
| **Drought** | - Prolonged periods of drought deplete soil moisture and water availability, severely affecting both rainfed and irrigated crops. | - Increasing the soil's capacity to retain water, through practices that lead to the increase of organic matter in the soil (biochar, mulching);<br>- Crop change and rotation;<br>- Management and conservation of resources<br>-The use of cover crops;<br>- Use of biofertilizers, stimulators,<br>-Irrigation<br>- Cloud seeding;<br>- Increase in relative water content, soil protein, antioxidant enzyme activity, sugars through the use of microorganisms | Hunter, 2021; Sarma, 2024; Ali, 2017; Zhang, 2020; He, 2024; Tăbărașu, 2024a; Dastogeer, 2018; Vílchez, 2018; Chaín, 2020; Paul, 2024; Sharan, 2024; Nenciu, 2021b |
| **Flood** | - Increased rainfall and flooding can damage crops, wash away nutrient-rich soil, and disrupt planting seasons.<br>- High-intensity storms can cause significant physical damage to crops, uproot plants, and damage critical agricultural infrastructure. | - Rational land management,<br>- Use of drainage ditches, storm drains, embankments, dams;<br>- Planting green belts, leguminous plants or other plants adapted to excessive water stress such as rice, willow, reed, etc.<br>- For nutrient losses, perennials with long root roots can be used, which also stabilize the soil | Jager, 2020; Schilling, 2019; McCarthy, 2021; Jager, 2018; Tiend, 2024; Careers, 2023; Nenciu, 2022d |
| **Pests and diseases** | - Warmer temperatures and humidity create ideal conditions for many agricultural pests and diseases to thrive.<br>- Climate change is allowing pests and diseases to spread to new areas. | - Modified Integrated Pest Management (IPM) practices.<br>- Modified cultivation practices and adapted management strategies: planting more varieties, planting at different times of the year, increasing biodiversity at the edges of the field to reduce the number of natural enemies<br>- The use of allelochemicals and pheromones, bioinsecticides. | Barzman, 2015; Lamichhane, 2015; Shrestha, 2019; Heuskin, 2011; Nihal, 2020; Stan, 2022; Alfizar, 2024; Nitta, 2024; Priya, 2024; |
| **Soil health and fertility** | - Increased temperatures and erratic rainfall can exacerbate soil erosion, degrade soil structure, and reduce organic matter content.<br>- Heavy rainfall can lead to nutrient leaching, where essential minerals like nitrogen and phosphorus are washed out from the soil. | -Seed bombing on difficult or inaccessible terrain, such as steep slopes or remote areas, which are difficult for traditional planting methods. This method is useful in carbon sequestration, rapid ecosystem recovery, reduced erosion and improving soil health accelerates the reforestation process.<br>- Conservation agriculture technology by reducing the degree of soil disturbance and diversification of plant species, preservation of crop residues from the previous year on fields before and after planting new crops.<br>- Improving soil health and fertility by using biofertilizers, compost, biochar, mulch.<br>- Precision soil fertilization using various smart methods. | Sarma, 2024; Rosmawati, 2023; Talukdar, 2023; Dutta, 2023; Cordovil, 2020; Nenciu, 2014 a, b; Kong, 2024; Mohawesh, 2021; Hernandez-Charpak, 2024; Calcan, 2022 |

| | | | |
|---|---|---|---|
| **Changing growing seasons** | - With unpredictable seasonal changes, farmers may have difficulty timing their planting and harvesting.<br>-Temperature changes can disrupt the timing between crop flowering and pollinator activity such as bees, reducing pollination success and crop yield. | - Crop improvement through the integration of biotechnologies.<br>- Use of simulated historical crop calendars.<br>- Adjustment of sowing dates.<br>- Using Computer Crop Simulation (CSM) methods, productivity ca be assessed by using physiological processes in relation to factors affecting production.<br>- Conservation of pollinators through strategies such as: integrated pest and pollinator management (IPPM); crop rotation; including a wide range of plants for different flowering times, sustainable pest control strategies. | Shamim, 2024; Minoși, 2022; Annie, 2023, Lundin, 2021; Guzmán, 2019; Sidhu, 2016; Long, 2016; Agbehadji, 2023; Ortiz-Bobea, 2021; Yoon, 2020 |
| **Impact on animal productivity** | -Changes in crop productivity have a direct impact on the availability and price of animal feed.<br>-Rising temperatures negatively affect animal health, reproduction and productivity. | - Using new climate-resistant crops<br>- Improving growth practices by improving nutrition, assisted reproduction strategies, etc.<br>- Reducing greenhouse gases by implementing different technologies and practices for carbon sequestration, improving diets to reduce enteric fermentation and using fertilizers more efficiently | Soumya, 2022; Jawhar, 2024; Llonch, 2017; Rojas-Downing, 2017; Sossidou., 2014 |

- **Synthesis and contextualization of validated solutions to combat the effects of climate change**

The solutions identified in the literature are largely convergent, however they are often adapted and contextualized to address the particularities of specific agro-ecological settings and thematic domains. This reflects the recognition that while the fundamental mechanisms of soil restoration and climate change mitigation are widely understood, their effective implementation requires tailoring to local biophysical conditions, socio-economic realities, and institutional capacities. In the following section, the most prevalent and empirically validated solutions reported in the scientific literature are systematically assessed and synthesized, which have demonstrated substantial potential to deliver long-term benefits in mitigating the adverse impacts of climate change on agriculture and soils. An overview of these solutions is presented in Table 2.

**Table 2**

**Key mitigation measures reported in the literature for addressing the impact of climate change in agriculture**

| No. | Recommended measures | Action | References |
|---|---|---|---|
| 1. | **Management of agricultural practices, no-till systems** | These measures include improving soil organic content, improving farmland management methods, improving indigenous genetic diversity, optimizing livestock farming techniques, integrating cropping and livestock systems, using diversified cropping methods, improving grazing land management, increasing agricultural productivity, mitigating soil erosion, and implementing agroecological techniques; use of planting and weed control technologies without tillage. | Yin, 2024; Dmuchowski, 2024; Liebhard, 2022; Vlăduț, 2024; |
| 2. | **Land/soil and water management** | Adaptation to climate fluctuations is facilitated by the implementation of sustainable land management approaches, such as conservation agriculture, agroforestry, sustainable intensification and optimized cropping systems.<br>The use of sustainable agriculture through integrated methods of managing pests and soil fertility, as well as better and more efficient use of water and nutrients. | Khatav, 2024; Hatfield, 2001; Tume, 2024; Ungureanu, 2020 |
| 3. | **Crop diversification and optimization of the harvesting system** | A reasonable and cost-effective approach to increase the resilience of the agricultural system to climate change is crop rotation, and the use of a variety of production methods is essential to ensure ecosystem regulation. For example, soil erosion control, greenhouse gas emission reduction, nutrient cycling, carbon sequestration and control of hydrological processes. | Magesa. 2023; Dawood, 2024; Nenciu, 2022c, d; Chamberlain, 2020; Huggins, 2007 |
| 4. | **Sequestration of organic carbon from the soil** | Annual cropping systems can capture unused carbon. In addition to reducing greenhouse gas (GHG) emissions, negative emissions (NET) technologies, also known as active removal techniques of $CO_2$ from the atmosphere, are needed to achieve net decreases in $CO_2$ and prevent the most dangerous consequences of climate change. Agricultural soils have the capacity to store all the $CO_2$ in the atmosphere, even though the level of carbon in the soil has obviously decreased in the last century. | Eckardt, 2023; Northrup, 2021; McClelland, 2021; Ogle, 2019; Nazir, 2024 |

| No. | Recommended measures | Action | References |
|---|---|---|---|
| 5. | **Development of resistant varieties** | Climate-resilient crops and varieties offer farmers a way to cope with climate change. Under new environmental conditions, these crops have a better yield, avoiding decreased productivity and crop failure | Kopeć, 2024; Matei, 2020; Nenciu, 2022 a, b |
| 6. | **Remote sensing and satellite imagery** | The impact of climate change on agriculture can be predicted using remote sensing. For example, satellites equipped with sensors can be used to monitor vegetation and determine different indices. | El Jazouli, 2019; Kazemi Garajeh, 2023; Beeson, 2016 |
| 7. | **Use of cover crops, crop residues, mulch, compost and biochar** | In conservation agriculture, the use of cover crops is one of the basic tasks. Plant species known as cover crops are introduced into crop rotations to provide benefits to the agro-ecosystem. Cover crops can be grouped according to the role they play on the farm. They can be annuals and function as live mulch, grown either alternately or at the same time as the crop. They have a role in improving porosity and aeration and drainage of the soil, reduce nitrogen losses and help sequester carbon. The use of mulch, crop residues and biochar have proven to be beneficial for both the soil and the crop. | Zhou, 2018; Hively, 2020; Mesgaran, 2017; Sun, 2019; Dissanayaka, 2024; Yousefi, 2024; Yuan. 2022; Gholizadeh, 2021; Sachdev, 2023; Safari, 2022; Agegnehu,2016; Mak-Mensah, 2021 |

This synthesis provides a foundation for informed decision-making and strategic planning, linking scientific knowledge to actionable pathways for resilience and sustainability. In the next sub-chapters, a selection and evaluation of the most significant case studies with empirically validated outcomes have been undertaken to analyze recent advancements in mitigating the adverse effects of drought and enhancing the quality and functionality of agricultural soils. These case studies were chosen based on their demonstrated efficacy and relevance across diverse agroecological contexts. Specially integrated solutions that combine cutting-edge technological innovations with sustainable land management practices were selected. This approach addresses immediate drought-related challenges and promotes long-term soil resilience and productivity.

- **Solutions, equipment and technological systems for mitigating the impact of drought and restoring agricultural soils**

As climate change accelerates and intensifies the frequency and severity of droughts, the urgency for innovative and integrated solutions to preserve and restore soil health has never been greater. Traditional farming practices, while productive in the short term, have often contributed to soil degradation, diminishing its ability to retain water, store nutrients, and support resilient crop growth. This degradation undermines the natural buffering capacity of soils against climatic extremes and threatens long-term agricultural productivity. Addressing these challenges requires a shift toward sustainable soil and water management practices supported by modern equipment and advanced technological systems.

This section explores a range of scientifically validated strategies and technologies that have proven effective in mitigating the adverse impacts of drought while enhancing soil quality and functionality. These include conservation agriculture techniques such as no-till and strip-till systems, precision irrigation equipment designed to optimize water use efficiency, and soil amendments like biochar and organic composts to improve soil structure and water-holding capacity. Additionally, the adoption of sensor-based monitoring systems, geographic information systems (GIS), and decision-support tools enables real-time assessment of soil moisture, fertility, and crop health, facilitating targeted interventions and efficient resource allocation. By integrating such solutions and technologies into agricultural practices, farmers can improve the resilience of agroecosystems, reduce vulnerability to drought, and promote the restoration and long-term sustainability of agricultural soils. This holistic approach not only safeguards productivity in the face of climate stress but also contributes to broader environmental and food security goals.

✓ ***Biochar production technologies and its role in mitigating the impact of drought***

Many studies (*Yuan et al., 2019; Patwardhan et al., 2022; Guo 2021; Malyan et al., 2021; González-Pernas et al., 2022 etc.*) have suggested biochar, (a carbon-rich substance obtained from the pyrolysis of different organic materials), as a possible technical option to deal with the numerous problems caused by drought in agricultural activities. Its characteristics have a significant impact, particularly in arid and semi-arid locations, and improve soil fertility and water retention in specific settings. In order to produce biochar, biomass must be thermally decomposed in a low-oxygen environment, turning organic molecules into a stable form of carbon. This method can lower greenhouse gas emissions, aid in the absorption of carbon, and turn agricultural waste into a useful soil amendment.

Biochar can be added to soil to greatly improve its chemical and physical characteristics, such as increased microbial activity, nutrient retention, and porosity.

This section examines different approaches for producing biochar, the technology tools needed, and the systems that make it easier to use in agricultural settings. The ways in which biochar helps restore degraded soils and lessens the effects of drought is evaluated, emphasizing its significance in supporting sustainable farming methods (*Vlăduțoiu et al., 2025*).


**Fig. 4 - Equipment for biochar production to enhance soil moisture retention**

*Technologies used in biochar production*

Biochar is a solid carbon-rich product obtained by heating biomass raw materials in a controlled process, with or without a limited oxidizing agent. In general, carbon makes up about 70% of the weight of biochar. In addition to the mineral components in the ash, the remaining fragments include hydrogen, sulfur, oxygen, nitrogen. The operating conditions, the characteristics of the raw material and the technologies used in the production process are just some of the many factors that influence the performance and properties of biochar (*Anton-Herrero et al., 2018; Li et al., 2018; Wang et al. 2020; Diatta et al. 2020).*

Biochar can be obtained from a variety of organic sources, mainly wheat straw, corn straw, wood chips, melon seed shell, peanut shell, rice husk, biomass energy crops, agricultural waste, manure, sewage sludge, organic kitchen waste, and so on (*Patwardhan et al., 2022; Tanet al., 2017*).

In general, biochar is produced through different thermochemical conversion processes, under different process parameters. The main processes of obtaining biochar are: slow pyrolysis, rapid pyrolysis, torrefaction and gasification (*Leng et al, 2019*).

*Slow pyrolysis* is described as a process in which the decomposition of biomass occurs at a relatively moderate temperature, in an oxygen-limited or oxygen-free environment, with typical heating rates between 1 and 30 °C min -1 (*Lua et al, 2004*). The name slow refers to a low rate of heating. Through the slow pyrolysis process, pyrolysis vapors are released from biomass and exhibit both condensable and non-condensable components. These components are collected in the form of by-products. The condensable components can be recovered in the form of bio-oil, which is also called "wood vinegar", the name coming from the acetic acid content (*Setter et al., 2020*).

*Rapid pyrolysis* is carried out at very high heating rates of up to 1000 °C/min. In this rapid pyrolysis process, the biomass undergoes rapid decomposition resulting in the generation of pyrolysis vapor and biochar (10-15%). In other words, in the rapid pyrolysis process, the main product obtained is bio-oil, and biochar is a by-product (*Choi et al., 2017*).

*Gasification* is the process by which biomass undergoes incomplete combustion. This process occurs at temperatures between 700-1000 °C in the presence of gasifying agents. These agents can be air, pure oxygen, or steam and oxygen to obtain a gaseous product (*Benedetti et al., 2018*).

*Torrefaction* is a heat pretreatment process that improves biomass properties. The main chemical roasting process develops in the absence of oxygen to obtain a solid product that is used as a solid fuel or as a soil amendment. Torrefied biomass that has a lower O/C ratio compared to the original biomass (*Barskov et al., 2019*). Typically, the spinning process is achieved by directly or indirectly heating the biomass to temperatures between 200 and 300 °C at a low heating rate of up to 50 °C/min over a period of time between 20–120 min (*Wang, et al., 2017*).

Biological charcoal has different physical and chemical properties, depending on the thermochemical parameters of operation and the intrinsic nature of the biomass. In order to achieve a higher yield and a better quality of the desired product, several plants, furnaces and reactors were built for the production of biomass. Although these reactors have a common principle, the oxygen use, heating rate, and final temperature are different. This can affect the quality and distribution of final products.

Regardless of the biochar equipment used, the main stages of the production process are the same: shredding the biomass, carbonizing it at different temperatures to obtain the biochar, cooling the biochar (*Zaman et al., 2017; Antal et al., 2003*).

*Biochar mechanisms for drought mitigation and soil restoration*

Agricultural productivity has long been affected by inefficient land management practices, climate change and unsustainable use of fresh water. To reduce the impact of climate change on agricultural crops and stop or reverse desertification and the systematic loss of food quantity and quality, farmers can manage healthy soils without using harmful chemicals. Regenerative management methods, such as minimal tillage technologies, cover crops and mulching, microorganism inoculation, nutrient cycling, organic fertilizer balance, or foliar application, help manage healthy soils (*Popescu et al., 2022*).

Recognized as a promising product for carbon storage, biochar improves soil's ability to retain nutrients and water, creates energy-dense energy carriers, and improves the environment by reducing greenhouse gas emissions (*Safarian et al. 2022*).

The redefinition of contaminated soil was carried out using a variety of remediation techniques, including chemical leaching, adsorption and immobilization, electrochemical remediation, phytoremediation, bioremediation, and others. Of these, the biochar adsorption technique is considered a promising technology for remediation of in situ immobilization. This is because it is easy to use, very effective, and environmentally friendly (*Gholizadeh et al., 2021; Sachdeva et al., 2023; Lin et al., 2021*).

First, biochar occurs in the soil in the form of loose discrete particles that are not bound to the soil. Subsequently, it interacts with the different parts of the soil to form denser and more stable complexes that are involved in the soil preparation process. Biochar can be mixed with different soil components in different ways. Soil micro-agglomerates are then formed from these organic-mineral complexes by electrostatic attraction, salt bridge, and van der Waals forces (*Nkoh et al., 2021*). Finally, biological secretions serve as binders to grow micro-agglomerates in the soil, and as a result, stable macro-agglomerates are formed in the soil. Despite the complexity of the process of biochar involvement in soil agglomerates, adhesion patterns between biochar and soil components can be observed during the formation of agglomerates by the use of scanning electron microscopy (SEM) (*Bai et al., 2020*).

Biochar also has the ability to physically adsorb and chemically interact with soil elements, resulting in an organic-mineral complex (*Sun et al., 2021*). To form a porous organic-mineral complex, functional groups C and N on the surface of the biochar interact with multivalent iron oxide particles (*Archanjo et al., 2017*). Finally, electrostatic attraction, salt bridge, and van de Waals forces cause these organic-mineral complexes to merge.

In other words, biochar, through its interactions with soil components, has the ability to influence the formation of soil aggregates. The interaction between biochar and soil components is based on seven possible mechanisms. These mechanisms can be listed as follows: the first is ligand exchange and electrostatic attraction between biochar-negatively charged functional groups and positively charged mineral surfaces; the second is ligand exchange and electrostatic attraction between negatively charged soil minerals and positively charged mineral surfaces; and the third is the hydrophobic and electro-phobic interaction between soil organic matter (SOM)/microorganism the fourth is the relationship between biochar, soil minerals and SOM/soil microorganisms and dissolved organic carbon (DOC); fifth, electrostatic interactions and ligand exchange between SOMs/soil microorganisms and positively charged minerals; sixth, electrostatic interactions that take place between negatively charged soil minerals, multivalent ions and negatively charged biochar; and seventh, electrostatic interactions between positively charged mineral surfaces, multivalent ions, and negatively charged biochar functional groups (*Nkoh et al., 2021; Yuan et al., 2022; Deng et al., 2022; Bai et al., 2020*).

Various studies have shown that biochar is used to combat the effects of climate change, to remediate soils that have been contaminated with potentially toxic elements (PTE); it is used to immobilize PTEs, improve soil quality, and increase crop yields. The effect of PTE adsorption of biochar is influenced by two main factors: the choice of raw material and the pyrolysis temperature of biological charcoal. Also, the application dose and incorporation time determine the remedial effect of biological charcoal in the soil (*Bousdra et al., 2023; Ji et al., 2022; Golia et al., 2022; Calcan et al., 2022; Hussein and Alaa Hasan 2024; Osman et al., 2024*).

Even though the number of studies referring to biochar is increasing, research on its long-term effects on the environment has been far fewer than in other areas of research, such as its use as a soil improver. To better understand how aging due to abiotic and microbial processes in soil will affect the C-sequestration capacity of biochar, further research is needed. This is because the results of specific field studies differ from those of corresponding field studies due to differences in soil properties under actual environmental conditions *(Singh et al. 2022*).

In general, most studies on the soil-biochar relationship are carried out either in a laboratory or in a greenhouse setting, and less in the field. For this reason, it is imperative to carry out additional field experiments. When it comes to assessing the effects of biochar on soil properties, most studies have been conducted in less than two years (*Zeba et al., 2022*).

- ✓ ***New tillage technologies and equipment designed to mitigate the impact of drought and restore agricultural soils***

Most of the main causes of soil degradation are natural, such as climate change (soil degradation caused by wind, sun, drought or heavy rains that favor fertile soil washing) and human activities (overgrazing, deforestation, excessive use of chemical fertilizers, pesticides, herbicides, bare soils, overconsumption of groundwater, etc.) (*Popescu et al. 2022a; Popescu et al., 2022b*).

Nowadays, the main theme of agricultural discussions is to increase productivity so that it matches or exceeds traditional tillage systems in terms of energy efficiency, water conservation, soil conservation, and crop quality. As tillage directly influences the stability and susceptibility of the soil to erosion, tillage is essential for the production of agricultural crops. Despite the fact that traditional soil tillage methods are more widespread, both in Europe and in Romania, a number of studies and practical applications have shown that systems with minimal tillage are effective. In contrast to traditional soil cultivation methods, soil conservation work is a method that has a significant carbon absorption effect and uses agricultural machinery that is more friendly to both the soil and the environment (*Bogdan et al., 2024; Li et al., 2024*).

Currently, to meet the water needs for irrigation, diesel and electric pumps are used; however, these traditional systems are inefficient and expensive. In these circumstances, it is imperative to develop new methods of crop irrigation that are both economical and less harmful to the environment. Such a model is the prototype made by INMA Bucharest in collaboration with ROLIX IMPEX SERIES SRL. The innovative prototype of the system includes a photovoltaic panel frame, a 2000kg two-axle automotive platform, several 85Ah gel solar batteries, a 5kW off-grid solar inverter, a Lorentz PS2-1800 CS-F4-6 solar pump, a PS2-1800 CS-F4-6 pump controller, an intelligent irrigation management and scheduling system, and a helix vertical wind turbine, 1000W, 600 rpm. The system can be quickly transferred to rural areas where there is no other source of electricity, and the pumping of water for irrigation is carried out by a photovoltaic surface pump, reducing the annual costs of a diesel motor pump (*Mateescu et al., 2023*).

*Conservation soil tillage equipment and methods*

The main methods for mitigating soil degradation due to climate change and agricultural practices are: conservative tillage; biological fertilization; directly sowing or in narrow strips; biological control of weeds, diseases and pests.

Regenerative agriculture refers to organic farming that uses natural resources exclusively. It is a sustainable farming method that involves growing healthy plants and restoring soil fertility. This creates healthier soils that are less sensitive to current. Regenerative agriculture technologies reduce drought and flooding, improves soil structure and fertility, increases water retention and crop yields, and carbon sequestration in the soil (*Dougherty et al., 2019; Li et al., 2024; Sapkota et al., 2015*).

Given that there is in a period when the water crisis and the effects of climate change are the most important risks, electric or solar-powered machines are increasingly used.

With a contribution of more than 20% of global greenhouse gas emissions, 42% of methane and 75% of nitrogen oxides (NOx), the agriculture and forestry sector are primarily responsible for these emissions. In addition, emissions at farm gates are anticipated to increase over the next few years. Most of these pollutants come from tillage and intensive animal husbandry, but much of it also comes from internal combustion engines (ICE), which are the most common sources of energy in the agricultural and forestry industry.

Various prototypes of electric tractors have been debated in the literature (*Matache et al., 2020; Engström et al., 2018; Ueka et al., 2013; Melo et al., 2019; Rossi et al., 2021; Yes et al., 2019*) from tractors with only electric motors, fully electric tractors, to unmanned hybrid electric tractors (*Gonzales-de-Santos et al., 2016; Beligoj et al., 2022*), but only few of them have ended up being launched on the market.

Farmers are willing to pay more for a safe vehicle rather than a cleaner or more efficient vehicle because reliability is the most important. The main benefits of hybrid technology and electric vehicles, such as fuel economy and reduced exhaust emissions, are not the main reasons influencing purchasing decisions. But eventually, due to the lack of fossil fuels and the spread of agriculture, electric tractors will become the dominant technology in the agricultural industry in the long term (*Scolaro et al., 2021*).

The success of any tillage operation lies in the use of modern agricultural plows, conservation techniques and alternative seeding systems. Finding an innovative and unique solution for modifying the construction and operation of the agricultural plough in order to maintain performance and, in particular, to significantly reduce fuel consumption and therefore $CO_2$ emissions is a priority. That is why the innovative vibration system for ploughs is also a method of soil conservation. The vibration system for ploughs with bodies in operation and production consists of a new electromagnetic vibration solution and innovative electronic control elements. It reduces the traction force of agricultural ploughs depending on soil conditions, rainfall level and thermal regime (*Croitoru et al., 2016; Croitoru et al., 2017; Ungureanu et al., 2015*).

*Innovative strategies to increase soil fertility*

To contribute to soil biodiversity and serve as a food source for soil fauna, soil organic matter serves as a reservoir of nutrients such as nitrogen, phosphorus, and sulfur. To facilitate the penetration of roots into the soil, organic carbon in the soil improves the physical environment and supports soil structure. As part of soil organic matter, organic carbon is essential for all processes that take place in soil. The earth's ability to bind water and handle large amounts of rainfall is also crucial for adapting to climate change. The annual rate of organic matter loss varies considerably depending on a variety of factors, including, but not limited to, cultivation methods, type of plant or crop cover, soil drainage status, and weather conditions.

In arid and sandy natural soils, organic matter serves as an "oxygen balloon" for vegetation, absorbing about six times its weight. Soils with organic matter have more complex structures, which improves water infiltration and reduces the likelihood of water compacting, eroding, deserting, and sliding off the ground (*Manea et al., 2023; Rumpel et al., 2020*).

Recent land use and climate change have led to a loss of soil organic carbon, accounting for 10% of Europe's fossil fuel emissions. Therefore, one of the most important strategies for increasing soil fertility is *carbon capture* (*Lorenz et al., 2014; Cooper, et al. 2021*).

Another strategy is *the use of cover crops*. During periods when there are no cash crops, cover crops are commonly grown between the main crops to cover them and keep the plants alive on the ground. This can be done either by planting cover crops after harvest or by sowing too many profit crops, usually cereals, with perennial crops that will develop to maintain soil cover after harvest the following season (*Wagg et al., 2021*).

It is assumed that the use of cover crops with multiple species, including legumes, improve various ecosystem functions. These functions include microbial diversity, biological nitrogen fixation, compaction reduction, beneficial insect attraction, weeds suppression, soil temperature regulation, and water infiltration increase. In addition to improving soil fertility, cover cropping helps to sequester carbon. The widespread adoption of these practices could reduce greenhouse gas emissions from agriculture by 10%. This compares to using no-till cultivation or other cultivation methods (*Kaye et al., 2017; Chahal et al., 2020*).

A current strategy for increasing soil fertility is the use of digitized techniques. By providing improved management systems, digitalization can help farmers increase soil fertility and reduce pollution. For example, "precision agriculture" uses satellite guidance systems to create permanent pathways for machinery to move, while "traffic-controlled agriculture" uses digital crop monitoring to apply the ideal quantity of pesticides and nutrients to crops at the right time. Therefore, agricultural traffic cannot reach cultivated land. Water and air circulation in the soil is improved and the top layer of soil is less compacted, leading to more stable yields during periods of drought or heavy rainfall (*Manea et al., 2023*).

✓ ***Bioremediation solutions***

*Microbial solutions for improving the quality of agricultural soils*

Soil biodiversity encompasses a wide variety of living organisms, including microbes and meso-, macro- and megafauna. Due to the complex interactions they have, biodiversity plays an important role in the functioning of the ecosystem. Regenerative agriculture practices focus on improving the capacity of soil microbes. This helps to recover the fertility of the affected soil, which is 70% of the world, to create healthier and more nutritious food and to fight climate change. The soil microbiota is essential for nutrient cycling, soil fertilization, and the breakdown of organic materials. Microbes in the soil also play an important role in growing healthy soil. An excellent indicator of how well an ecosystem works across the globe is soil strength. Soils with higher microbial diversity are more resistant to disturbance and more resilient than soils with lower microbial biodiversity (*Wagg et al., 2014; Wagg et al., 2019*).

The application of microbial populations and isolation to remediate heavy metal ions in the environment was a particular point of interest, as they have the ability to effectively highlight pollution problems. Microbial populations, mainly bacteria and fungi, have acquired various heavy metal retention mechanisms, making them good candidates for bioremediation (*Tirri et al., 2017*). It has been pointed out that there are numerous bacterial species that support plants in soil remediation, such as: *Pseudomonas*, *Bacillus*, *Variovorax*, *Klebsiella*, *Sinorhizobium*, *Enterobacter*, *Rhodococcus*, *Flavobacterium*, *Ensifer* and *Kocuria* (*Asad et al., 2019; Zhu et al., 2023; Guo et al., 2020; Wang et al., 2024*) or fungi such as: *Rhizophagus*, *Trichoderma, Beauveria bassiana,* Glomus *versiforme* (*Yang et al., 2021; Arriagada et al., 2009; Gola et al., 2021*).

A new model of soil fertility based on biology is the soil food web. It is a better model because it costs less, does not cause disease, does not pollute and uses fewer chemicals. Microorganisms are the intermediaries between water, plants and nutrients. Plants control the soil's viable food web and exudates through the consumption of carbohydrates and proteins. In addition, they attract certain bacteria and fungi. At the bottom of the soil food web are bacteria and fungi that consume root exudates. Even in the rhizosphere, bacteria and fungi are consumed by larger microbes, nematodes, and protozoa and are excreted as nutrients. Arthropods eat protozoa and nematodes. Arthropods can be eaten by other arthropods, or they can be eaten by snakes, birds, moles, and other animals. Worms, insect larvae, and moles move through the ground in search of food, building paths that allow water and air to enter.

To help create soil structure, components of the soil's food web bind soil particles together, creating tunnels for air and water. The soil food web is a natural design and has seven major advantages. These include preventing disease, retaining nutrients, increasing the availability of mineral nutrients to plants, improving soil structure, breaking down toxic chemicals, growing production plants, and improving crop quality. Root growth hormones are released by microorganisms and other members of the food web in the soil. These growth hormones help plants cope with the current or a flood and help them produce more (*Lowenfels et al., 2010*).

✓ ***Phytoremediation strategy for the management of contaminated soils***

The sustainable phytoremediation method uses plants to improve polluted environments, such as agroecosystems. New approaches have been reported that use the plant microbiome in remedial processes. Plants can more effectively sequester, degrade, or stabilize contaminants by using this microbial assistance to remediate soils contaminated with heavy metals such as As, Pb, Cd, Hg, and Cr. Some plant species are notable for their hyper-accumulative properties, which work well with their microbial partners and can mitigate heavy metal pollutants. This sustainable biotechnology based on plant-microbe associations improves biodiversity, improves soil structure, and promotes plant growth and health, making it a promising solution to the problem of agricultural pollution globally (*Zhu et al., 2023; Manoj et al., 2020*).

To remove organic and inorganic chemicals from polluted areas, there are a variety of phytoremediation technologies, including phytoextraction, phyto-stabilization, phytodegradation, phytovolatilization, rhizo-filtration, and rhizo-degradation. Different phytoremediation methods depend on the level of cleaning, the type of pollutant, the types of plants and the condition of the site (*Iacov et al., 2018*). Several species with well-developed root systems have the ability to absorb large amounts of pollutants, especially HM, and then transfer them to the leaves and shoots using a sweat pump powered by solar energy. Thus, toxic substances close and are deposited in metabolically inactive cell spaces, such as the vacuole, cell membrane, and cell wall, of the aerial parts, without causing damage to the body as a whole. About 700 species of trees, herbs and shrubs mainly from the *Brassicaceae* family, but also others such as *Euphorbiaceae, Asteraceae, Lamiaceae, Poaceae Scophulariaceae, P. vittata, Thlaspi caerulescens, B. napus, A. bertolonii, S. alfredii and P. American*: *Brassica napus, Brassica juncea, Cannabis sativa, Sinapis, Nicotiana tabacum, Miscanthus spp., Sorghum bicolor, Lemna minor,* etc. are recognized as hyper accumulative plants (*Pruteanu et al., 2018; Pruteanu et al., 2019; Pruteanu et al., 2020; Meers et al., 2005; Brunetti et al., 2011; Barbosa et al., 2015; Nsanganwimana et al., 2014; Xiao et al., 2021; Tăbăraşu et al., 2023; Osman et al., 2023*).

- **Renewable energies and technologies that optimize resource consumption in agriculture**

Nowadays, different industries frequently use renewable resources to meet their energy needs. Renewable energy can be used in agriculture for various activities. It can shed light on many problems that have arisen as a result of our dependence on fossil fuels, such as the reduction of fossil fuel reserves, increased spending, harmful effects on the environment, and so on. In the long term, the use of renewable energy in agriculture will help overcome these problems, leading to higher profits and more independence. Energy from these renewable sources can be used for a longer period of time without depleting natural resources. Solar, biomass, wind, and geothermal energy are all renewable energy sources available in agriculture (*Yaqoob et al.2023, Voicea et. al. 2024*).

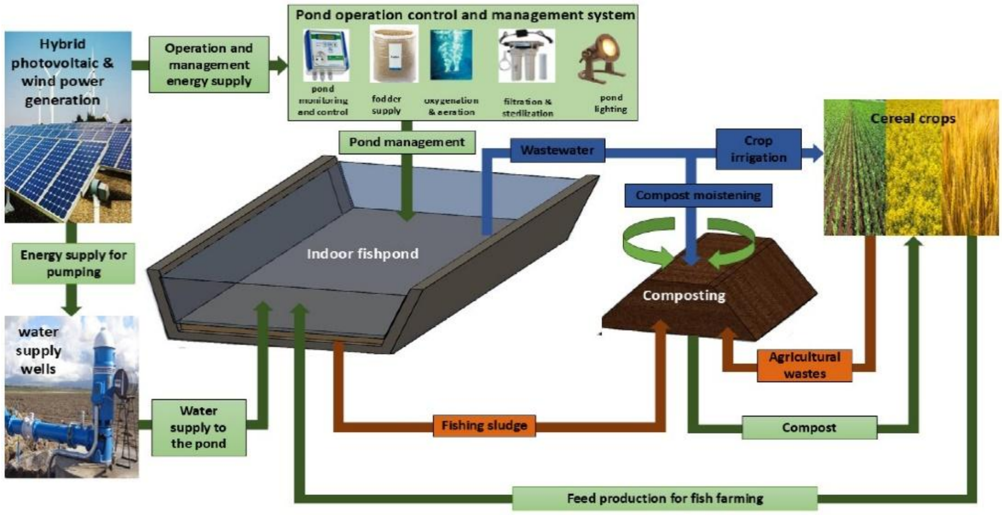


**Fig. 5 - Self-Sufficiency Approach within a Sustainable Integrated Pisciculture Farming System**
(*Voicea et. al., 2024*)

Agricultural activities traditionally rely heavily on fossil fuels, making the transition to renewable sources essential for reducing greenhouse gas emissions and ensuring long-term environmental sustainability. Solar energy systems, such as photovoltaic panels, are increasingly deployed to power irrigation pumps, greenhouse heating, and farm machinery, offering clean and cost-effective alternatives (*Hoogwijk, 2004*). Similarly, wind energy is utilized on farms both for local electricity consumption and for contributing with the surplus energy to the grid. Biogas production from livestock manure and crop residues not only provides a renewable energy source, but also addresses waste management and nutrient recycling challenges (*Hasan et al., 2019a, 2019b*). Hybrid systems that combine solar, wind, and biogas technologies enhance the reliability of energy supply by making use of multiple renewable resources. On-site renewable energy generation improves the energy self-sufficiency of farms and supports the adoption of modern technologies such as precision agriculture tools, automated systems, and environmental monitoring devices *(Baidya Roy and Traiteur, 2010*). Moreover, investments in renewable energy systems can create additional economic opportunities through the sale of excess electricity and the generation of carbon credits (*Armstrong et al., 2014*). Energy-efficient designs and the integration of renewable sources help reduce production costs while maintaining or improving productivity.

Overall, the adoption of renewable energy systems in agriculture supports a transition towards more resilient, economically viable, and environmentally responsible food production systems (*Harris et al., 2014; Sanz et al., 2017; Aschilean et al., 2018*).

## CONCLUSION

Global warming affects soil in a number of ways, including soil damage, loss of organic matter, soil compaction and salinization, drought, and flooding. The principles of conservation agriculture can benefit the soil. The structure of the soil depends primarily on cultivation, especially ploughing, which breaks up the soil and destroys earthworm tunnels, which are essential for drainage and water retention. Direct drilling has been shown to increase transit capacity, reduce long-term soil compaction, reduce wind and water erosion, reduce water evaporation, and increase water availability in the soil. Also, due to its low energy consumption, direct drilling reduces investment in machinery and improves planting and harvesting time. Crop residues reduce the use of herbicides, as they suppress weed growth.

Recent literature highlights several critical steps to accelerate the global and local adoption of climate-smart agriculture (CSA). These include developing comprehensive climate-alert strategies, integrating climate change risks into national policy agendas, and empowering farmers through targeted education and training programs. A particularly effective strategy for implementing CSA is the adoption of precision agriculture, leveraging advanced tools such as information technology, geographic information systems (GIS), and remote sensing. These technologies enhance the efficiency of agricultural inputs while providing valuable, high-resolution data on crops, soils, and climatic conditions. Such data-driven insights enable informed decision-making and the selection of optimal cropping strategies that mitigate the adverse impacts of climate change. Ultimately, a coordinated approach combining policy, education, and technology is essential to build resilient agricultural systems and ensure sustainable food production in the face of a changing climate.

Studies shown that implementing various soil health measures (such as maintaining permanent or increased soil cover, minimizing soil disturbance through reduced or no ploughing, and adopting conservation tillage practices like no-till or strip-till), represents a cornerstone of sustainable agriculture. When combined with the strategic use of cover crops and diverse crop rotations, these practices deliver multiple agronomic, ecological, and economic benefits. Improved soil structure and enhanced organic matter content contribute to greater water infiltration and retention, thereby increasing drought resilience and buffering crops against extreme weather events. Conservation practices also promote soil biodiversity, foster nutrient cycling, and reduce erosion, which collectively sustain or even improve long-term agricultural productivity. Furthermore, by reducing soil carbon losses and enhancing sequestration, these approaches lower greenhouse gas emissions and improve the overall environmental footprint of farming systems. Integrating these scientifically proven soil health strategies into mainstream agricultural management is critical for building resilient agroecosystems capable of meeting the growing global demand for food while safeguarding natural resources and mitigating the impacts of climate change.

The studies found that farmers should regularly incorporate organic matter, such as compost or green manure, alongside biochar into their soils to enhance fertility, structure, and moisture retention over time. This combined approach not only improves nutrient availability and microbial activity, but also promotes long-term carbon sequestration, contributing to more resilient and sustainable soil health. Consistent application, tailored to specific soil conditions and crop needs, will maximize these benefits.

The primary limitation of this study lies in the considerable diversity of methodologies, experimental conditions, and assessment metrics reported across the reviewed studies, which complicates direct quantitative comparisons between the evaluated technologies.

Long-term studies of soilless tillage are needed to see how they affect soil compaction, carbon sequestration, soil erosion, soil temperature due to mulch cover, water infiltration and their impact on global warming.

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